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High-frequency Percussive Ventilation in Patients with Inhalation Injury

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Inhalation injury complicated by bacterial pneumonia is now one of the primary causes of morbidity and mortality in patients with thermal injury. We have investigated the use of high-frequency percussive ventilation (HFPV) as a means of ventilatory support for these patients. We propose that high-frequency ventilation may decrease the incidence of pulmonary infection following inhalation injury and decrease the incidence of iatrogenic barotrauma caused by conventional ventilation.

High-frequency ventilation was instituted initially as salvage therapy in a group of five patients. In each case, normocapnia or arterial pO_2 saturation of greater than 90% on a FIO_2 of 60% or less was achieved with high-frequency ventilation but not with conventional ventilation. A second group of ten patients was prospectively entered into a study on the use of HFPV in patients with inhalation injury. One patient was removed from the study, and one patient was unable to be ventilated because of severely noncompliant lungs. Eight patients with a mean age of 29 years and a mean burn size of 38% of the total body surface completed the protocol. All patients survived, two developed pneumonia, and one developed subcutaneous emphysema. These results suggest that HFPV is effective in the treatment of patients with severe inhalation injury.

Inhalation injury frequently accompanies thermal injury and increases the mortality of burned patients. Bacterial pneumonia, a common sequel of inhalation injury, is now the primary cause of morbidity and mortality in patients with such injury (14). Inhalation injury complicated by pneumonia increases burn-associated mortality up to a maximum of 60% in relation to age and extent of burn (18).

Current treatment for patients with severe inhalation injury involves supportive care with conventional volume-cycled positive pressure ventilators, supplemental oxygen, and standard methods of tracheobronchial toilet. Systemic antimicrobial treatment is dictated by the results of sputum microbiology and is administered to patients who develop pneumonia. To date, no treatment modality including steroids and prophylactic antibiotics has altered the mortality of severe inhalation injury (13, 21).

High-frequency ventilation has been shown to be effective in several clinical and laboratory trials (1–3, 6–8, 17). The usefulness of this method of ventilatory support, having several potential advantages over conventional mechanical ventilation, remains undefined in burned patients. The ability to ventilate and oxygenate patients at lower peak and mean airway pressures should result in less airway and parenchymal barotrauma. Additionally, the ability to adequately oxygenate patients at lower levels of inspired oxygen may decrease the morbidity associated with a higher FIO_2. Last, limited clinical experience with high-frequency ventilation in patients with inhalation injury has shown that the clearance of secretions from the tracheobronchial tree is dramatically increased (20).

To date, we have found no study that has specifically addressed the role of high-frequency ventilation in patients with inhalation injury. This paper describes our initial experience in the use of HFPV in 15 patients with moderate to severe inhalation injury.

METHODS

Patient Population. Fifteen patients admitted to the U. S. Army Institute of Surgical Research between December 1986 and February 1988 form the basis of this study. Inhalation injury was confirmed in each patient by bronchoscopy and Xenon scan. The presence of erythema and ulcerations was used to define moderate to severe inhalation injury. Patients with significantly positive Xenon scans but normal bronchoscopy are defined as having mild inhalation injury. This classi-

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fication schema is based upon our previously published review (18).

Group I consists of five patients in whom high-frequency ventilation was initiated as salvage therapy. Each patient failed conventional, mechanical ventilatory support using either a Bear II or Seimens 900C ventilator. In each case the ability to maintain normocapnia or an arterial O_2 saturation of greater than 90% on a level of inspired oxygen of less than 70% was impossible with conventional ventilation.

Group II consists of the first ten patients who were enrolled in an ongoing prospective study of the use of high-frequency ventilation in inhalation injury. Criteria for entry into this group are listed in Table I. Each patient upon entry into the study met standard criteria for the need of mechanical ventilation (Table II). Mechanical ventilation was instituted with the high-frequency ventilator within 24 hours of intubation.

High-frequency Percussive Ventilation. HFPV was delivered by a high-frequency pulse generator (Bird Space Technologies, Percussionaire Corp, Sand Point, ID). Gas from the high-frequency pulse generator is delivered through a nongated sliding venturi connected to a standard endotracheal tube. The venturi entrains humidified gas from a fresh bias gas flow provided from the ventilator. The system combines a series of high-frequency subdeadspace volume breaths with a variable I:E ratio. Initially the I:E ratio for the subtidal volume breaths is 1:1. Periodic interruption of high-frequency pulsatile flow is programmed to allow return of airway pressure to baseline CPAP. The ratio of the duration of the percussive phase to the duration of baseline CPAP is adjusted as a means of manipulating oxygenation and CO_2 elimination. Additionally, peak airway pressure can be adjusted to maintain adequate CO_2 elimination. The frequency of the subdeadspace breaths was maintained between 200 and 600 breaths per minute. FIO_2 and PEEP were adjusted to maintain an O_2 saturation greater than 90%.

In Group I each patient's peak airway pressure, FIO_2, PEEP, pCO_2, and pO_2 were compared before and after the initiation of high-frequency ventilation. In Group II the incidence of clinically significant barotrauma, the incidence of pneumonia, and ultimate outcome were recorded.

RESULTS

Group I. Five patients were treated with HFPV as salvage therapy. The patient characteristics are listed in Table III. Blood gas data just before and after 6 hours of HFPV are shown in Table IV. Before its institution, each patient had demonstrated either progressive hypoxemia or CO_2 retention, unresponsive to alterations in FIO_2, PEEP, I:E ratio, and minute ventilation. Each patient underwent multiple manipulations of mechanical ventilatory support dependent upon whether hypoxemia or CO_2 retention was present. Attempts to improve oxygenation included increased levels of PEEP (up to 25 cm H_2O), inversed I:E ratios, and increases in FIO_2. Attempts to improve CO_2 clearance included increases in respiratory rate up to 40 breaths/minute, alterations in peak flow, and increases in tidal volume (up to 15–18 ml/kg). Despite considerable blood gas improvement following initiation of HFPV, each patient eventually died.

Group II. From March 1987 to February 1988, ten patients meeting inclusion criteria were entered into a prospective study of the use of HFPV in patients with inhalation injury. Inhalation injury was diagnosed by bronchoscopy in each patient and was considered moderate to severe in nature. One patient was removed from the study upon the request of the attending physician and one was switched back to conventional mechanical ventilation because of the inability of the high-frequency ventilator to deliver adequate inspiratory pressures (greater than 120 cc of water). Seven patients completed the protocol, and one patient is currently still on it. Patient data are presented in Table V. The mean age of these eight patients was 29 years (range, 19–60) with the extent of burn varying from 10–65% of the total body surface ($\bar{x} = 38$). The average number of ventilator days was 11, with a range from 4 to 30 days. The only clinically

TABLE I
Inclusion criteria

1. Age > 18 years
2. Admission to burn unit <48° postburn
3. Less than 48° conventional mechanical ventilatory support
4. Documented inhalation injury by Xenon scan or bronchoscopy
5. Clinical need for mechanical ventilation

TABLE II
Indications for intubation and mechanical ventilation

1. Respiratory rate > 30
2. PaO_2 < 60 on FIO_2 > 40%
3. Minute ventilation > 20 L/min
4. PCO_2 > 45 or PCO_2 < 45 but progressively increasing
5. Severe laryngeal edema
6. Severe facial burns

TABLE III
Group I patient characteristics

Case No.	Age (yrs)	Sex	% Burn	PBD/ HFPV*	Complications
1	4	Male	43.5	18	Pneumonia
2	63	Male	67.5	16	Pneumonia, sepsis
3	2	Male	42.5	1	—
4	1	Female	59	11	Pneumonia
5	5	Male	75	12	Pneumonia

* Postburn day HFPV was instituted as salvage therapy.

TABLE IV
Group I patient data

Case No.	FIO_2	PIP (cm H_2O)	PEEP (cm H_2O)	PaO_2/FIO_2	PaO_2	$PaCO_2$
1	1.0/0.5*	50/38	7/5	63/172	63/86	57/37
	1.0/0.45	50/50	10/10	103/228	103/103	158/70
2	1.0/0.5	65/50	10/2	149/236	149/118	46/48
3	1.0/0.4	40/20	10/5	60/352	60/141	51/32
4	0.7/0.4	70/70	10/10	140/325	98/130	77/40
5	1.0/0.6	75/65	20/3	36/105	36/105	55/27

* Conventional/HFPV. Each data set represents the best obtainable ventilator settings and blood gas levels for each patient.

TABLE V
Group II patient data

Age (yrs)	Sex	% TBSB	Barotrauma	Pneumonia	Predicted Mortality	Days
27	Female	56	(—)	(+)	65%	17
35	Male	36.5	(—)	(—)	35%	4
20	Male	50.5	(—)	(—)	55%	5
20	Male	38	(—)	(—)	35%	12
31	Female	31	(—)	(—)	25%	6
19	Male	17	(+)	(—)	20%	7
19	Male	10	(—)	(—)	20%	7
60	Male	65	(—)	(+)	79%	30 (+)
$\bar{x}$ 29		38%			44%	11

evident barotrauma was subcutaneous emphysema in one patient. Two patients developed pneumonia. All patients survived.

DISCUSSION

When inhalation injury accompanies cutaneous burns, mortality is disproportionately higher than that predicted by the extent of cutaneous injury alone (5). This synergistic effect is most apparent in patients with burns, associated with a 40–60% mortality. Inhalation injury alone results in a maximum 20% increase in mortality. The incidence of bacterial pneumonia is greatly increased by the presence of inhalation injury, with 38% of patients with an inhalation injury developing pneumonia compared to 8.8% of burned patients without inhalation injury. When inhalation injury was moderate to severe (i.e., diagnosed by bronchoscopy), 48% developed pneumonia. The addition of pneumonia to inhalation injury results in a maximum 60% increase in mortality for this group of patients (18).

The pathophysiology of inhalation injury is complex and not fully understood. Extensive tracheobronchial injury may result in sloughing of the respiratory tract mucosa and impairment of the normal mucociliary clearance mechanism. Slough of the mucosa results in cast formation which obstructs moderate sized airways, leading to distal atelectasis, or a ball valve effect, leading to distal air trapping and increased barotrauma. Disruption of endothelial and epithelial integrity permits exudation of protein-rich plasma into terminal airways which serve as media for bacterial overgrowth and subsequent development of pneumonia. Injury to Type II pneumocytes impairs surfactant production and contributes substantially to the pathologic process. The parenchymal changes are associated with hypoxemia and hypercarbia due to the shift of the ventilation-perfusion relationship to the left (i.e., an increase in lung segments with V/Q ratios greater than 0 but less than 1). This change in V/Q has been adequately documented in animal models of inhalation injury (19).

The goal of any new treatment regimen for inhalation injury should be the reversal of these pathophysiologic changes. A second and equally important goal is that the treatment causes no further injury. For patients with moderate to severe injury who require mechanical ventilation, current conventional ventilators do not accomplish either of these goals. Clearance of secretions is not enhanced, and the complications of high inflation pressures and high FIO_2's compound the existing injury. The goal of ventilator therapy should be adequate oxygenation on a nontoxic FIO_2 and CO_2 clearance at the lowest possible inspiratory pressures with maintenance of functional residual capacity above closing volume. Better clearance of secretions and a shift of the V/Q mismatch back to the right are also desirable. Various reports have concluded that high-frequency ventilation may accomplish all of these goals (1, 3, 7, 8, 11, 15, 16, 20).

The major characteristics of high-frequency ventilation include a ventilatory frequency greater than 60 breaths per minute, tidal volumes of less than dead space, lower peak airway pressures than conventional ventilation, positive endotracheal pressures throughout the ventilatory cycle, lower transpulmonary pressures than in conventional ventilation, increased FRC, possible less circulatory interference than with conventional ventilation, and more efficient pulmonary gas distribution than with conventional ventilation (8). These characteristics of HFV should make it the ideal form of ventilatory support for patients with significant inhalation injury but it should be noted that each of these reported advantages has been refuted in various reports (9, 10, 12).

The safety of high-frequency ventilation has been documented in several reports. Its use in postoperative general surgery and cardiac surgery patients has demonstrated no untoward hemodynamic effects (17). Peak airway pressures and mean airway pressures are reduced and several studies have demonstrated decreased pulmonary shunt flow with the use of this type of ventilatory support. Two recent reports have documented the effectiveness of short-term salvage use of high-frequency ventilation in patients with ARDS (7, 8). Oxygenation was improved and adequate CO_2 clearance was maintained in each patient.

In 1986, Carlon reported a series of 309 patients who were randomized to high-frequency jet ventilation or conventional ventilation, respectively (4). Mortality from underlying disease was quite high in that study; however, the pulmonary dysfunction was not severe. Mean ventilator time was 2.5 days. Peak airway pressures were lower in the high-frequency group compared to the conventional ventilation group. There was a 4% incidence of barotrauma in each group. Overall outcome did not differ between the two groups. Standard high-frequency jet ventilation at a rate of 100 breaths per minute and an I:E ratio of 1:2 was used in each patient. The only manipulated variable was driving pressure. In an attempt to standardize the ventilatory support for each patient, the versatility of high-frequency jet ventilation was not utilized (i.e., frequency and I:E ratios were not altered to obtain the best possible results).

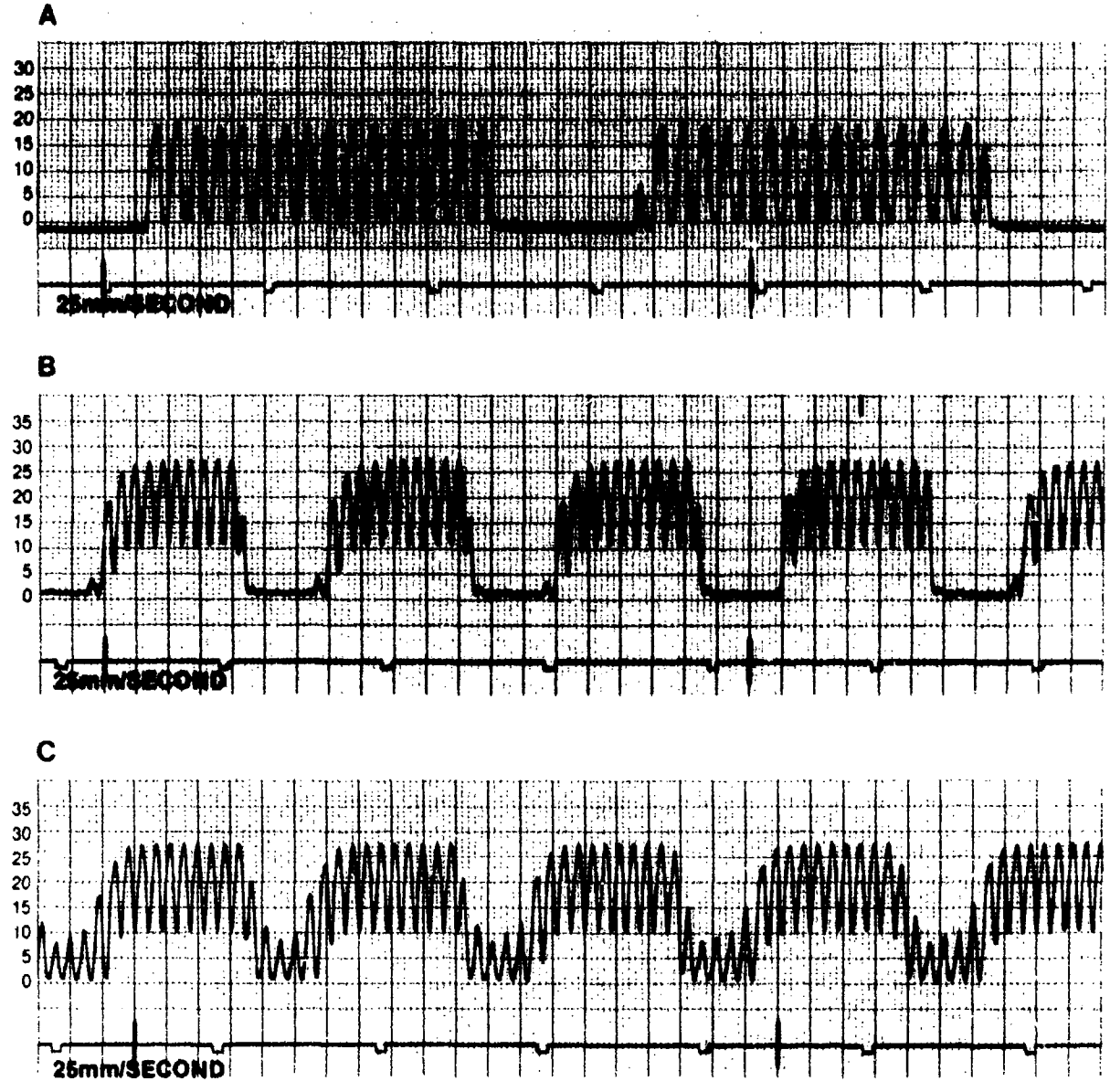

FIG. 1. Representative wave form tracings from proximal airway using HFPV. A) Standard wave form with periodic interruption of pulsatile flow. B) Same as A with higher inspiratory pressures and increased convective gas flow. C) Same as B with institution of oscillatory positive end expiratory pressure during period of interruption of pulsatile flow.

HFPV is an exceptionally versatile form of HFV in which high-frequency subtidal breaths are superimposed upon conventional ventilation (Fig. 1). This ventilator combines the entrainment mechanism of high-frequency jet ventilation with the ability to manipulate airway pressure in a phasic manner.

In this study we have demonstrated the superiority of HFPV compared to conventional ventilation in maintaining adequate CO_2 clearance and oxygenation in a critically ill group of burned patients with severe respiratory insufficiency (Group I). For this group of patients, recommendations of optimum ventilator settings cannot be made. For both conventional and high-frequency ventilators, all ventilator settings were manipulated to achieve the best possible oxygenation and CO_2 clearance at the lowest possible peak inspiratory pressures and PEEP values. In this small group of severely ill patients, even though ventilation was improved, mortality from multiple organ failure was not altered. At the time HFPV was instituted in each patient as salvage therapy, at least two other systems besides pulmonary had already failed.

This ventilator is difficult to monitor and difficult to use. However, with proper education of house staff and respiratory therapists, its use is feasible. The results from the prospective use of high-frequency ventilation in the Group II patients are favorable. The degree of pulmonary insult was moderate to severe in all patients as assessed bronchoscopically. Using data collected from an historical cohort treated at this Institute between 1980 and 1985, one would predict an approximate 40% mortality

for the Group II patients (18). Additionally, approximately one half of the patients should have developed pneumonia. In actuality, all patients survived and only two developed pneumonia during their hospital course. Although no firm conclusions can be drawn because of the small number of patients in Group II, a favorable trend is noted. To determine whether high-frequency ventilation significantly improves survival, approximately 50 study patients will be needed.

The results of this study support but do not confirm the opinion that HFV is effective in the treatment of patients with severe ARDS. Although it is unlikely that HFV represents a panacea for all forms of respiratory failure, the results in the Group II patients suggest that HFV will be useful in the treatment of patients with severe inhalation injury. The study patients are different than those with severe ARDS in that their insult is acute in nature and, given the proper circumstances, should go on to heal in 10 to 21 days. If during this period of spontaneous airway repair, one can provide adequate ventilatory support, not increase the risk of barotrauma, and at the same time facilitate clearance of the airway secretions and debris resulting from the injury, one may be able to decrease the morbidity and mortality associated with inhalation injury.

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